

# Cooperative Multiplexing in a Half Duplex Relay Network: Performance and Constraints

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**Abstract**—Previous work on relay networks has concentrated primarily on the diversity benefits of such techniques. This paper explores the possibility of also obtaining multiplexing gain in a relay network, while retaining diversity gain. Specifically, consider a network in which a single source node is equipped with one antenna and a destination is equipped with two antennas. It is shown that, in certain scenarios, by adding a relay with two antennas and using a successive relaying protocol, the diversity multiplexing tradeoff performance of the network can be lower bounded by that of a  $2 \times 2$  MIMO channel, when the *decode-and-forward* protocol is applied at the relay. A distributed D-BLAST architecture is developed, in which parallel channel coding is applied to achieve this tradeoff. A space-time coding strategy, which can bring a maximal multiplexing gain of more than one, is also derived for this scenario. As will be shown, while this space-time coding strategy exploits maximal diversity for a small multiplexing gain, the proposed successive relaying scheme offers a significant performance advantage for higher data rate transmission. In addition to the specific results shown here, these ideas open a new direction for exploiting the benefits of wireless relay networks.

## I. INTRODUCTION

Generally speaking, a relay network can act as a virtual multiple-input multiple-output (MIMO) system if the nodes are allowed to cooperate [1], [5], [6]. It is well known that a MIMO system has two advantages over single-input single-output systems, namely multiplexing gain and diversity gain. The diversity gain can improve the system outage performance (i.e., reliability), while the multiplexing gain enhances the spectral efficiency for high SNR. The tradeoff between diversity and multiplexing gain is a key characteristic of MIMO systems [2]–[4], and hence for relay networks (virtual MIMO systems). The optimal diversity-multiplexing trade-off (DMT) for half-duplex relay networks is yet to be discovered [5], [6], especially in the scenario in which multiple antennas can be deployed at one node. However, instead of looking at both multiplexing and diversity behavior simultaneously, most of the past work emphasizes primarily the diversity benefits of the relay network (e.g. [1]), while ignoring the possible multiplexing benefits it could bring. Unlike a point-to-point MIMO link, in a half-duplex relay network, multiplexing gain is difficult to obtain due to the additional transmission time slots the relays require. In fact, it has been shown recently [6] that no multiplexing gain (of more than 1) can be achieved for

high SNR in general, when the source is deployed with only one antenna, even if *full-duplex* relay transmission is assumed. We note that, compared with full-duplex relaying, half-duplex relaying is recognized to be a suboptimal but more practical choice for wireless networks.

As one might hope that relaying could bring both diversity and multiplexing gain, investigating and realizing this possibility is of significant importance. Very recently, some capacity analyses [7], [8] on *scalar channels* have shown that *only under certain signal to noise ratio (SNR) constraints*, is it possible to achieve a MIMO rate through *full-duplex* relaying. However, the DMT for these SNR values in fading environments is not exploited and discussed in these papers.

In this paper, we show that it is even possible to obtain multiplexing gain in a *half-duplex* relay network. We consider a scenario in which the relays perform decode-and-forward. Specifically, we consider a one-antenna source, a two-antenna relay, and a two-antenna destination. We apply a *successive relaying* protocol to make the two antennas at the relay transmit in turn. We show that in this scenario a DMT that is at least as good as that of a  $2 \times 2$  MIMO channel can be obtained under certain finite SNR or channel constraint. Based on our network model, we show that the constraint can be expressed by an upper bound for the SNR and a function of the channel coefficients. We also show that the above DMT can be achieved with a very high probability for most of the realistic SNR values, in a scenario in which the relay is close to the source. We also develop a more practical signalling method, which we refer to as the distributed D-BLAST architecture, to achieve the  $2 \times 2$  MIMO DMT lower bound. Furthermore, we derive a space-time coding scheme, which can also offer a multiplexing gain of more than 1, provided that the source to relay channel is good enough. We discuss the constraints for this scheme and compare it with the successive relaying scheme. While the space-time coding strategy exploits maximal diversity for a small multiplexing gain, the successive relaying scheme offers significant performance advantages for higher data rate transmission (i.e., higher multiplexing gain).

The decode-and-forward successive relaying scheme has been discussed for single antenna relay networks [9], [10], while neither of the above works explore the possibility of obtaining multiplexing gains of more than 1 by using such a

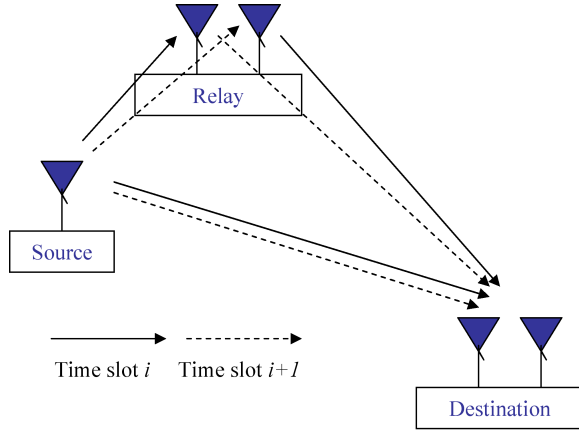


Fig. 1. Network model.

scheme. We note that the difference between our work and [9], [10] is that we use *independent Gaussian codebooks* at the relays to re-encode the message, instead of using the same codebook as at the source. In fact, in our work the additional multiplexing gain is obtained through *distributed coding*.

The rest of the paper is organized as follows. In Section II, the system model and transmission protocol are introduced. In Section III, the DMT performance for the proposed scheme is analyzed. In Section IV, a distributed D-BLAST signalling method is proposed to approach the DMT bound obtained in Section III. The space-time coding scheme is discussed and compared with the proposed successive relaying scheme in Section V, and conclusions are drawn in Section VI. Due to limited space, we omit all the proofs of the theorems in the paper. Details of the proofs can be found in [11].

## II. SYSTEM MODEL AND PROTOCOL DESCRIPTION

We concentrate on a network in which there is one source having a single antenna, one relay having 2 antennas, and one destination having 2 antennas. We assume that the relay is close to the source, while both the source and the relay are far away from the destination<sup>1</sup>. Note that this assumption is made to facilitate the decode-and-forward relaying protocol. We split the source transmission into frames, each containing  $L$  codewords denoted as  $x_l$  ( $l = 1, 2, \dots, L$ ). Each  $x_l$  represents a different message. These  $L$  codewords are transmitted continuously by the source, and are decoded, re-encoded and forwarded by two antennas at the relay successively in turn. When the relay re-encodes the message, it uses a Gaussian codebook independent of the one used by the source. For example, in time slot  $i$ , the source transmits a codeword  $x_i$ , the destination and antenna 1 at the relay receive this codeword, while antenna 2 transmits a codeword  $x'_{i-1}$ , which represents the same message as the codeword  $x_{i-1}$  it received in the previous time slot  $i - 1$  but which is generated from an independent Gaussian codebook; in time slot  $i + 1$ , the source transmits another codeword  $x_{i+1}$  to the destination and

antenna 2 at the relay, while antenna 1 at the relay transmits a codeword  $x'_i$ , which represents the same message as  $x_i$  but generated from an independent Gaussian codebook, etc. Overall,  $L$  codewords are transmitted in  $L + 1$  time slots. A visual description for the network model and protocol is shown in Fig. 1. Note that in each time slot  $i$  ( $2 \leq i \leq L$ ) at the relay, one of the antennas is transmitting while the other is receiving. Here we make an important assumption that the interference between the antennas can be pre-subtracted, as the knowledge of the transmitted signal is known to both antennas at the relay.

## III. DMT ANALYSIS

We assume a slow, flat, block fading environment, in which the channel remains static for each message frame transmission (i.e.  $L + 1$  time slots). We denote the source as  $s$ , relay as  $r$ , destination as  $d$ , and the channel coefficient between the  $i$ th transmit antenna at node  $a$  and the  $j$ th antenna at the node  $b$  by  $h_{a_i,b_j}$ . Each  $h_{a_i,b_j}$  experiences independent and identically distributed (i.i.d.) Rayleigh fading. We will also consider other fading effects specifically later, such as path loss in Section III.B. Unless specifically stated, we assume that the transmitters do not know the instantaneous channel state information (CSI) on their corresponding forward channels, while CSI is available at the receivers on their receiving channels. We also assume that all transmit antennas transmit with equal power  $\eta^2$ . The white Gaussian noise at the receive antennas is assumed to be i.i.d. with zero mean and unit variance. First, we review the definition of the high-SNR DMT.

**Definition 1: (High-SNR DMT)** Consider a family of Gaussian codes  $C_\eta$  operating at SNR  $\eta$  and having rates  $R$ . Assuming a sufficiently long codeword, the multiplexing gain and diversity order are defined as

$$r \triangleq \lim_{\eta \rightarrow \infty} \frac{R}{\log_2 \eta}, \quad \text{and} \quad d \triangleq - \lim_{\eta \rightarrow \infty} \frac{\log_2 P_{out}(R)}{\log_2 \eta}, \quad (1)$$

where  $P_{out}(R)$  denotes the outage probability as a function of the transmission rate  $R$ .

We also review the maximal DMT that can be obtained *in general* for the system model described in Section 2.

**Theorem 1 ([6]):** The maximal DMT for the system model described in Section II (i.e., one single-antenna source, one two antenna relay and one two antenna destination) in half-duplex mode is  $d(r) = 4(1 - r)^+$ .

We note that this bound might be achieved by using a compress-and-forward protocol [6], which is distinct from the decode-and-forward protocol considered here.

### A. A Lower Bound for the Optimal DMT

In the following we will first assume that the relay can always correctly decode the message. We will remove this assumption later when considering the constraints on the source-relay link in Section III.B. After the relay correctly

<sup>2</sup>Note that this assumption is made for the sake of analytical simplicity; any power allocation will affect the system power gain but not the diversity multiplexing tradeoff at high SNR.

<sup>1</sup>More specific examples will be given and analyzed in section III and IV.

$$\underbrace{\begin{pmatrix} y_1^1 \\ y_1^2 \\ y_2^1 \\ y_2^2 \\ y_3^1 \\ y_3^2 \\ \vdots \\ y_{L+1}^1 \\ y_{L+1}^2 \end{pmatrix}}_{\mathbf{y}} = \sqrt{\eta} \underbrace{\begin{pmatrix} h_{s,d_1} & 0 & 0 & 0 & 0 & 0 & 0 \\ h_{s,d_2} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & h_{r_1,d_1} & h_{s,d_1} & 0 & 0 & 0 & 0 \\ 0 & h_{r_1,d_2} & h_{s,d_2} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & h_{r_2,d_1} & h_{s,d_1} & 0 & 0 \\ 0 & 0 & 0 & h_{r_2,d_2} & h_{s,d_2} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & h_{r_1(2),d_1} \\ 0 & 0 & 0 & 0 & 0 & 0 & h_{r_1(2),d_2} \end{pmatrix}}_{\mathbf{H}} \underbrace{\begin{pmatrix} x_1 \\ x_1' \\ x_2 \\ x_2' \\ x_3 \\ x_3' \\ \vdots \\ x_L \\ x_L' \end{pmatrix}}_{\mathbf{x}} + \underbrace{\begin{pmatrix} n_1^1 \\ n_1^2 \\ n_2^1 \\ n_2^2 \\ n_3^1 \\ n_3^2 \\ \vdots \\ n_{L+1}^1 \\ n_{L+1}^2 \end{pmatrix}}_{\mathbf{n}}, \quad (2)$$

decodes the message, it forwards the re-encoded symbol to the destination. The destination *waits until* it receives the entire message frame (i.e.,  $L$  symbols) in  $L + 1$  time slots, before it performs maximal likelihood (ML) decoding. The system input-output relationship, for each set of  $L + 1$  time slots, can be expressed as equation (2), where the vector  $\mathbf{y}$  is the  $2(L + 1) \times 1$  receive vector, the matrix  $\mathbf{H}$  denotes the  $2(L + 1) \times 2L$  channel transfer matrix,  $\mathbf{x}$  is the  $2L \times 1$  transmit vector, and  $\mathbf{n}$  is the  $2(L + 1) \times 1$  noise vector at the receiver. The scalar  $y_i^j$  denotes the signal received by antenna  $j$  in the  $i$ th time slot. The scalar  $x_i$  denotes the symbol transmitted by the source in the  $i$ th time slot, while  $x_i'$  denotes the symbol transmitted by the relay in the  $(i + 1)$ st time slot, which contains the same message as in  $x_i$ . The channel coefficients  $h_{r_1(2),d_i}$  in the bottom-right of  $\mathbf{H}$  could be either  $h_{r_1,d_i}$  (for odd  $L$ ) or  $h_{r_2,d_i}$  (for even  $L$ ). Finally, the scalar  $n_i^j$  denotes the received Gaussian noise at the  $j$ th antenna at the destination in the  $i$ th time slot. Regarding the DMT, we have the following theorem for this system.

**Theorem 2:** For sufficiently large  $L$ , the DMT for the system described in (2) is lower bounded by that for a  $2 \times 2$  point-to-point MIMO channel, i.e., the piecewise linear function (see Theorem 2 in [2]) connecting the points  $(n, (2 - n)^2)$ ,  $n = 0, 1, 2$ .

This result is surprising, as it implies that MIMO multiplexing gain can be obtained with only one (source) transmit antenna. The way to interpret this is that the multiplexing gain in this scenario is in fact obtained through distributed coding of the same information across both space and time. In this way, every piece of information is *multiplexed* into two separate (independently) encoded data streams in each of two successive time slots, while those two streams are received by two antennas (at the destination). This implies that a multiplexing gain of 2 can be obtained, once a reliable link between the two transmit antennas is established. The D-BLAST structure to be introduced later will give an operational interpretation for this system.

### B. Finite SNR DMT and Constraints

When we consider the source to relay channel constraint, we consider the more recent concept of the finite-SNR DMT,

which allows us to study the DMT for realistic SNRs. The definition of the finite DMT is given as follows [3].

**Definition 2: (Finite-SNR DMT)** The finite-SNR multiplexing gain  $r$  and diversity gain  $d$  are defined as

$$r = \frac{R}{\log_2(1 + g\eta)}, \quad \text{and} \quad d(r, \eta) = -\eta \frac{\partial \ln P_{out}(r, \eta)}{\partial \eta} \quad (3)$$

where  $g$  denotes an array gain achieved at low SNR, and  $P_{out}(r, \eta) = P$  is the outage probability at rate  $R = r \log_2(1 + g\eta)$ .

**Theorem 3:** Suppose the SNR satisfies the following constraint.

$$\eta \leq \frac{a - b - c}{bc}, \quad (4)$$

where

$$\begin{aligned} a &= \min \left\{ |h_{s,r_i}|^2 \right\} \\ b &= \left( |h_{s,d_1}|^2 + |h_{s,d_2}|^2 \right) \\ c &= \min \left\{ |h_{r_i,d_1}|^2 + |h_{r_i,d_2}|^2 \right\} \end{aligned}$$

for  $i = 1$  and  $2$ . Then, the outage probability for the network shown in Section II is lower bounded by

$$P_{out} \leq 2P_{2 \times 2} - P_{2 \times 2}^2, \quad (5)$$

where  $P_{2 \times 2}$  is the outage probability for a  $2 \times 2$  MIMO channel. The finite-SNR DMT for the proposed scheme performs approximately the same as that for a  $2 \times 2$  point-to-point MIMO channel.

There are two important notes about this corollary.

1) *Impact of network geometry:* One might think that the probability with which (4) holds is low in general. This is true. However, as widely indicated in the previous literature, it is well recognized that the decode-and-forward protocol performs well only when the source and relay are close to each other (e.g. [8]). Otherwise other relaying modes might be better choices (e.g. amplify-and-forward and compress-and-forward). In practice, the best way to perform decode-and-forward is to use a relay that is close enough to the source so that reliable communication between the source and relay can be established.

	Slot 1	Slot 2	Slot 3	Slot 4	Slot 5	Slot 6
Source	Code 1(1)	Code 2(1)	Code 3(1)	Code 4(1)	Code 5(1)	
Relays		Code 1(2)	Code 2(2)	Code 3(2)	Code 4(2)	Code 5(2)
	Relay 1	Relay 2	Relay 1	Relay 2	Relay 1	

Fig. 2. Transmission schedule.

Now, if we take the distance into account and consider the path loss<sup>3</sup>, it can be seen that (4) can be satisfied with high probability in many scenarios. Suppose, for example, that the distance between the source and the relay is  $\tilde{r}$ , while both source and relay are at unit distance from the destination (note that similar models have been used in previous analyses, e.g. [6], [7]). With a pathloss exponent of 4, which is commonly assumed in a terrestrial environment, the channel coefficients for source-relay links can be rewritten as  $\tilde{r}^{-2}h_{s,r_i}$ . The constraints (4) can be approximated as

$$\eta \leq \tilde{r}^{-4} \times \frac{a}{bc}. \quad (6)$$

It can be seen that as long as  $\tilde{r}$  is sufficiently small, the probability that (6) is satisfied is high. Simulation results relating to this probability are described in Section V.

2) *Adaptive protocol design*: The result offers many insights for practical adaptive protocol design. For example, if the relay (near the source) can be configured to retransmit the message only when it decodes the signal correctly, then a MIMO DMT can be obtained with high probability. Note that although it has been shown that a MIMO DMT is not possible for the network model shown in the paper *in general*, the proposed transmission and coding scheme offers MIMO DMT performance in many scenarios. Those scenarios are *not uncommon*, especially in an ad hoc network or uplink cellular environment.

#### IV. DISTRIBUTED D-BLAST

The DMT-tradeoff presented in *Theorem 2* might be obtained by using an Maximum-likelihood (ML) decoder at the destination, which is extremely complex for large values of  $L$ . A simpler decoder is thus desired. Carefully examining the proposed transmission and coding strategy, it can be found that the codes representing the same messages are layered diagonally in space and time. Fig. 2 illustrates this structure, in which codeword  $i(j)$  denotes the  $j$ th code for the  $i$ th message. Clearly this structure mimics a D-BLAST structure, which was originally proposed for point-to-point MIMO [12]. The only difference is that the messages are encoded in a distributed fashion at both the source and the relay. It has been shown that D-BLAST with minimal mean-squared error (MMSE) successive interference cancellation (SIC) is DMT-optimal for a point-to-point MIMO system [2]. We will also show here

that the distributed D-BLAST can achieve the same DMT as indicated in *Theorem 2*.

*Theorem 4*: For the system described in (2), the distributed D-BLAST structure with the MMSE SIC algorithm achieves the optimal DMT lower bound as indicated in *Theorem 2*.

Generally speaking, the performance advantage of the distributed D-BLAST lies in the use of parallel channel coding methods (e.g. the use of independent codebooks in the above analysis) for each message. We note that recently developed parallel channel codes for point-to-point MIMO systems might be applied directly to the distributed D-BLAST structure here (e.g., see the bit-reversal permutation codes in [13]).

#### V. COMPARISON WITH SPACE-TIME CODING

This scheme can be considered to be an extension of Laneman's scheme [1] to a multiple antenna scenario, and we term it the *space-time coding protocol*. In this protocol, transmission is divided into two time slots. In the first time slot, the source broadcasts the signal to the relay and destination. Each antenna at the relay uses an independent codebook to re-encode the message it received, and transmits the new codeword to the destination in the second time slot. Note that two independent codebooks are used at the relay in total. Assuming that the relay correctly decodes the message, the input-output relationship can be expressed as

$$\begin{pmatrix} y_1^1 \\ y_1^2 \\ y_2^1 \\ y_2^2 \end{pmatrix} = \eta \begin{pmatrix} h_{s,d_1} & 0 & 0 \\ h_{s,d_2} & 0 & 0 \\ 0 & h_{r_1,d_1} & h_{r_2,d} \\ 0 & h_{r_1,d_2} & h_{r_2,d} \end{pmatrix} \begin{pmatrix} x' \\ x'' \end{pmatrix} + \begin{pmatrix} n_1^1 \\ n_1^2 \\ n_2^1 \\ n_2^2 \end{pmatrix}, \quad (7)$$

where  $x'$  and  $x''$  denote the two codewords at the relay. We have the following theorem in terms of DMT for the system described in (7).

*Theorem 5*: On assuming that the relay correctly decodes the message, the high-SNR DMT for the system in (7) can be written as

$$d(r) = \begin{cases} 6 - 6r, & 0 \leq r \leq 1/2 \\ 5 - 4r, & 1/2 \leq r \leq 1 \\ 3 - 2r, & 1 \leq r \leq 3/2 \end{cases}. \quad (8)$$

This theorem shows that multiplexing gains greater than 1 can be obtained through space-time coding if multiple antennas are deployed at the relay. We note that this fact was not discovered in [1], which only considers a single antenna network. In fact, it was shown in [1] that the network suffers from a multiplexing loss (i.e. a multiplexing gain of less than 1) when the destination is deployed with only a single antenna, even if the message is correctly decoded at the relays. Therefore, we can conclude that deploying a single antenna at the destination is not sufficient to fully exploit the benefits of space-time coding. *Theorem 5* also indicates that the space-time coding scheme can outperform the DMT upper bound (in *Theorem 1*) that can be achieved *in general*, as long as the message is correctly decoded at the relay. Specifically, it can achieve a maximal diversity gain of 6 for zero multiplexing gain. However, in practice this assumption imposes constraints

<sup>3</sup>Note that adding path loss does not affect the DMT performance in general.

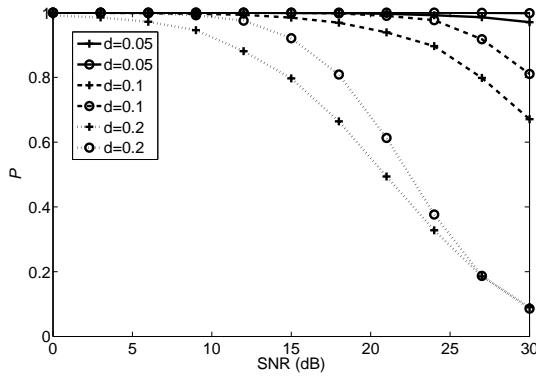


Fig. 3. The probability for (6) and (9) versus SNR ( $\eta$ ). The letter “d” denotes the distance between the source and relay (i.e.,  $\tilde{r}$ ). The curves with mark “+” denote the performance of the successive relaying scheme. The curves with mark “o” denote the performance of space-time coding.

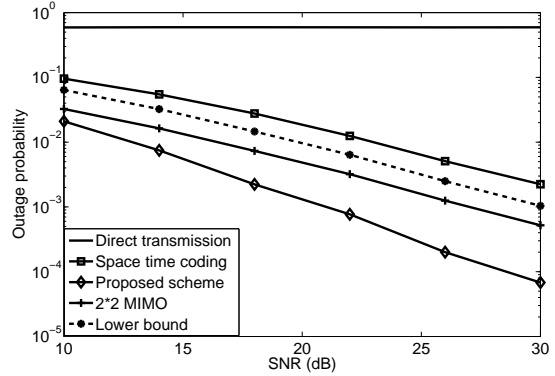
on SNR as well as source-relay channel conditions. Using the same channel model as indicated in Section III.B, these constraints can be approximated by the following bound (see [11] for details of the analysis):

$$\eta \lesssim \tilde{r}^{-4} \times \frac{p}{qz}, \quad (9)$$

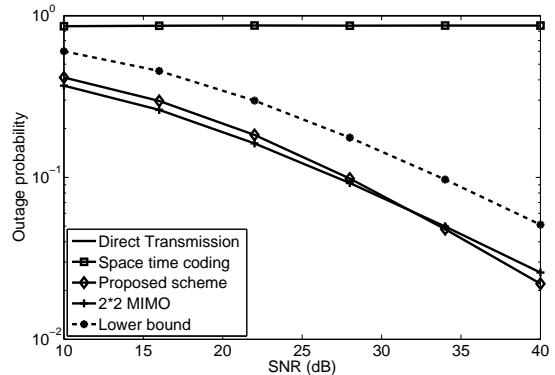
where  $p = |h_{s,r_1}|^2 + |h_{s,r_2}|^2$ ,  $q = (|h_{s,d_1}|^2 + |h_{s,d_2}|^2)$  and  $z = (|h_{r_1,d_1}|^2 + |h_{r_1,d_2}|^2 + |h_{r_2,d_1}|^2 + |h_{r_2,d_2}|^2)$ .

Fig. 3 shows the probability with which (6) and (9) hold for different value of  $\eta$ . It can be seen that when the source-relay distance is small (e.g.  $\tilde{r} = 0.05$ , or  $\tilde{r} = 0.1$  in the figure), the probability for both constraints is high even for an SNR value of 30dB, which is higher than in most practical applications. Note that the DMT performance in this SNR region approaches the high-SNR DMT as indicated in *Theorem 2* and *Theorem 5*. For a medium SNR level (e.g. 0-15dB), the probabilities approach 1. This means that the finite-SNR DMTs for the systems in (2) and (7) are almost *always* reached.

It is not straightforward to analyze the finite-SNR DMT for space-time coding. However, we expect from the conclusion in *Theorem 5* that space-time coding cannot perform better than the proposed successive relaying scheme for  $r > 1$ . Fig. 4, which reflect the finite-SNR DMT properties for different schemes, shows simulated values of the outage probability for different values of the multiplexing gain  $r$  when  $L = 20$ , while assuming the source-relay link is perfect. The “lower bound” curve represents the performance lower bound (5) for the proposed successive relaying scheme. Note that this is also a performance lower bound for the distributed D-BLAST scheme. We can observe from the figures that the lower bound is actually not very tight. The proposed scheme in fact offers much better performance. This might be because the successive relaying scheme can in fact offer a higher *diversity gain* than  $2 \times 2$  MIMO transmission (see the differences among the curves’ slopes), as it uses three antennas instead of two



(a)  $r = 1$ .



(b)  $r = 1.5$ .

Fig. 4. Outage probability for different schemes, when (a)  $r = 1$ , (b)  $r = 1.5$

antennas to transmit. It can be seen that for  $r = 1$ , the diversity gain for direct transmission is zero and so the curve has no slope. When  $r = 3/2$ , both direct transmission and space-time coding schemes have a diversity gain of zero, while the proposed scheme has a diversity gain at least as good as that of a  $2 \times 2$  MIMO system. This confirms the analysis in the paper and shows that the proposed successive relaying scheme can offer significant performance advantages over other schemes for higher data rates.

## VI. CONCLUSIONS

Unlike most previous work in wireless relay networks, which concentrates only on cooperative diversity, this work opens a new direction of exploiting the *cooperative multiplexing* in such networks. The results in the paper also suggest that distributed coding cannot only offer diversity, but also multiplexing gain as well. This discovery also implies a new direction for future network coding design. A number of interesting topics are left for future work: (a) exploiting more multiplexing benefits in the model discussed in the paper; (b) extending the model to more general cases in which every node is equipped with multiple antennas, or in which there are multiple relays; (c) extending the analyses to a multi-user environment, e.g. a multiple-access relay network; and (d) exploiting the possibility and constraints of obtaining

multiplexing gain by using other relaying modes, such as compress-and-forward.

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